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Load Capacity of Biaxially Loaded Reinforced Concrete Columns Confined with CFRP

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ABSTRACT: This paper presents results of an experimental investigation and analytical approach for prediction of the load capacity of reinforced concrete columns confined with carbon fiber reinforced polymer (CFRP) under axial load and biaxial bending. Eight specimens were constructed and tested; four specimens were tested under biaxial eccentric loading and four specimens were tested under concentric loading. The analytical approach accounts for the non-linear stress-strain behavior of both unconfined and CFRP-confined concrete. For a symmetric square cross-section with equal eccentricity about each principal axis, the column cross-section is discretized into finite layers. The sectional forces are integrated numerically and the load capacity is predicted using an iterative process. For a rectangular cross-section, the load capacity is determined using the reciprocal load equation. The CFRP-confinement was found effective in improving the structural performance under biaxial eccentric loading. A comparison between the analytical and experimental results demonstrated the validity of the analytical approach.

1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) wrapping system can provide confinement to concentrically loaded reinforced concrete (RC) columns thus improving the load carrying capacity and ductility (ACI 440.2R 2008; Hollaway L, Teng J 2008). The effectiveness of the CFRP wrapping to improve the structural performance of concentrically loaded RC columns is greatly affected by the cross sectional shape. The performance enhancement caused by the CFRP is much less pronounced for square and rectangular columns than for circular columns (ACI 440.2R 2008; Hollaway L, Teng J 2008). The efficiency of the CFRP wrapping to improve the structural performance of RC columns is also influenced by the loading condition. The CFRP wrapping system is less effective in improving the performance of eccentrically loaded RC columns than concentrically loaded columns (Chaallal & Shahawy 2000; Parvin & Schroeder 2008; El-Maaddawy et al. 2010). It was observed that the strength gain caused by the CFRP in eccentrically loaded RC columns is inversely proportional to the load eccentricity.

It is not unusual for RC columns to support axial load accompanied by bending about the two principal axes. Corner columns in RC buildings are typically exposed to an eccentric load causing biaxial bending. Biaxial loading condition is also developed in columns cast monolithically as a part of frames in both directions and/or columns supporting heavy spandrel beams. Bridge piers are also often exposed to simultaneous axial load and biaxial bending. The performance of RC columns wrapped with CFRP under combined axial load and biaxial bending has received little attention in the literature (Youcef et al. 2008; Punurai et al. 2009).

This paper is aimed at examining the viability of the CFRP wrapping system to upgrade RC columns exposed to biaxial eccentric loading. The main objectives are to provide experimental evidences for strength assessment of biaxially loaded RC columns wrapped with CFRP and to introduce a simple, yet accurate, analytical approach for prediction of the load capacity of RC columns wrapped with CFRP under axial load and biaxial bending.

2. EXPERIMENTAL INVESTIGATION

Two different cross sections were used in the present study (Figure. 1); square (135x135 mm) and rectangular (120x150 mm). The cross sections dimensions were selected so that both sections had almost the same cross sectional area. The test matrix is given in Table 1. A total of eight specimens were tested. The specimens were divided into two main groups, [A] and [B], according to their loading condition. Group [A] is composed of four specimens tested under concentric loading whereas group [B] is composed of four specimens tested under biaxial eccentric loading with nominal eccentricity-to-section depth ratio in the direction of each principal axis of 0.3 (i.e. $e_x/b = e_y/h = 0.3$, where e_x = eccentricity in x-direction, e_y = eccentricity in y-direction, b = section dimension in x-direction, and h = section dimension in y-direction). In each group, half of the specimens were fully wrapped with one layer of CFRP whereas the other half were kept unwrapped.

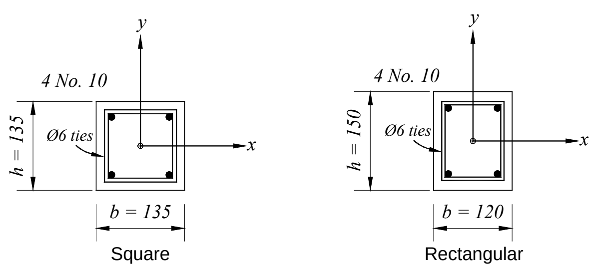


Figure 1. Cross sections shapes

Table 1.Test matrix

Group	Loading condition	Section shape	Confinement condition	Specimen name[a]
[A]	Concentric	Square	No-wraps	SN-e0
			CFRP-wraps	SF-e0
		Rectangular	No-wraps	RN-e0
			CFRP-wraps	RF-e0
[B]	Biaxial	Square	No-wraps	SN-eb
			CFRP-wraps	SF-eb
		Rectangular	No-wraps	RN-eb
			CFRP-wraps	RF-eb

2.1 Test Specimens

Layout of steel reinforcement is given in Figure 2. Specimens of group [A], tested under concentric loading, were in a form of short columns, each having a height of 480 mm. Specimens of group [B], tested under biaxial eccentric loading, had end corbels, each having a cross section of 300x300 mm and a length of 380 mm. The ratio of the length of the test region between the end corbels-to-section height (*l/h*) was kept constant at a value of 4 for both section shapes. The end corbels were designed to have flexural and shear strengths well in excess of the anticipated failure load of the column's section in the test region. All test specimens were reinforced by 4 No. 10 steel bars, one at each corner. The shear reinforcement in the middle 450 mm of all test specimens consisted of 6 mm diameter plain steel bars spaced at 150 mm on center. All strengthened specimens were fully wrapped with one layer of continuous CFRP laminate with the fibers oriented in transverse direction. The CFRP laminates had an overlap of 60 mm in transverse direction (the overlap length was about 50% of the cross section side dimension). Specimens of group [A] had an additional CFRP strip, having a width of 50 mm, at each end of the test region to avoid premature failure at these locations due to possible stress concentration. The corners of the cross sections of the strengthened specimens were rounded to a radius of about 10 mm prior to the application of the CFRP. A concrete with an average compressive strength $f_c^{'}$ = 20 MPa was used in the present study. The longitudinal steel reinforcement was Grade 520 whereas the shear reinforcement was Grade 300. The carbon fiber fabric (SikaWrap Hex 230C) was unidirectional having a tensile strength of 3.45 GPa, an elastic modulus of 230 GPa, and an elongation at break of 1.5% (information was extracted from the manufacturer data sheet. The fabric was laminated to the specimens with an epoxy resin (Sikadur 330) that has a tensile strength of 30 MPa and an ultimate elongation of 1.5%. According to the data sheet provided by the manufacturer, a cured CFRP composite sheet (including resin) typically has a thickness of 0.381 mm, an average tensile strength of 894 MPa, a tensile modulus of 65.4 GPa, and an ultimate elongation of 1.33%.

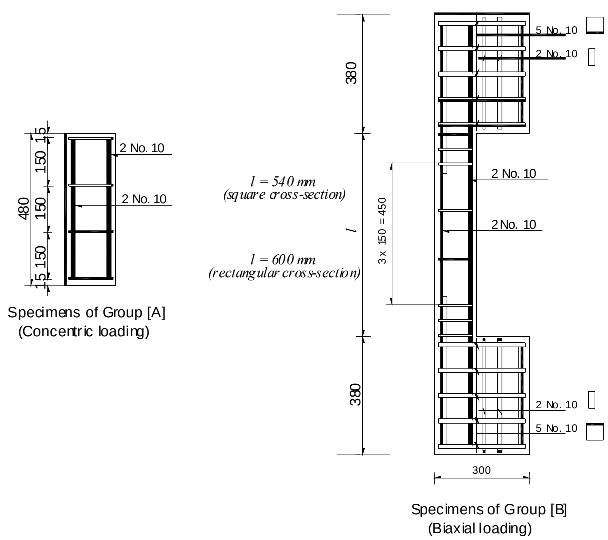


Figure 2. Test Specimens

2.2 Test Set-up

Specimens of group [A] were tested under concentric axial loading using a 5000 kN capacity universal testing machine. Axial strains were measured at the mid-height by means of a dial gage whereas electrical resistance strain gages were used in transverse direction at the mid-height to measure the transverse strains in the CFRP-wrapped columns. Specimens of group [B] were tested under biaxial eccentric loading using a 200 kN reaction frame. Load was applied on test specimens by means of a hydraulic jack and two loading plates: top plate with knife-edge and adaptor plate. V-notch grooves, skewed with respect to the principle axes, were cut through the adapter plate at desired angles to allow the biaxial loading application. Load was recorded by means of a load cell. Longitudinal and transverse strains were measured by electrical resistance strain gages whereas the lateral mid-height deflection was measured in each direction by means of Linear Variable Displacement Transducers (LVDTs) mounted on the concrete at the mid-point of the column.

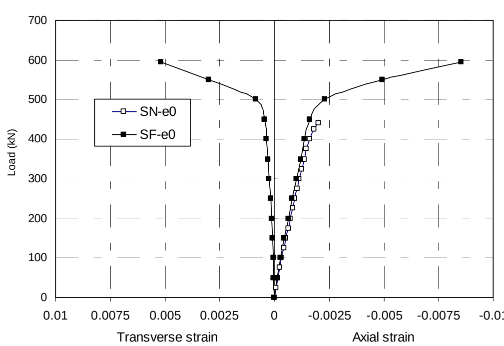
3. EXPERIMENTAL RESULTS

Under both concentric and biaxial eccentric loading conditions, the unwrapped columns failed by crushing of concrete and the CFRP-wrapped columns failed by rupture of CFRP in transverse direction. Failure modes under biaxial loading are shown in Figure 3. The load versus strain relationships of the concentrically loaded columns are depicted in Figure 4 and the load versus mid-height deflection relationships of the biaxially loaded columns are depicted in Figure 5. The load capacitates of the unwrapped columns under concentric loading were comparable because they had similar cross sectional area. From the figures, it is evident that CFRP-wrapping effectively improved the columns load capacity and ductility under both loading conditions. The performance enhancement was affected by the section shape. Under concentric loading, the square column exhibited about 35% strength gain whereas the rectangular column exhibited about 30% strength gain. The axial strain of the concentrically loaded CFRP-wrapped columns at peak load was on average four times that of the unwrapped columns. The CFRP transverse strain measured at the onset of rupture, under concentric loading, was on average 40% of the CFRP rupture strain from direct tensile tests which is 1.3%, as reported in the data sheet provided by the manufacturer.

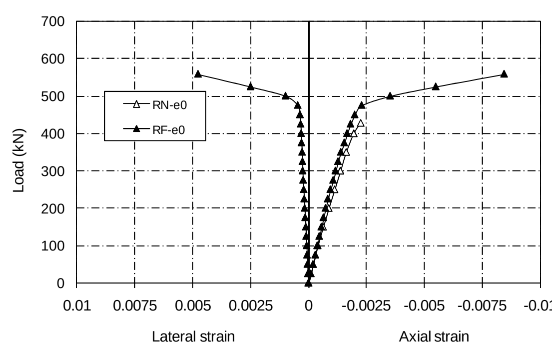
unwrapped specimen

wrapped specimen

Figure 3. Failure modes under biaxial loading

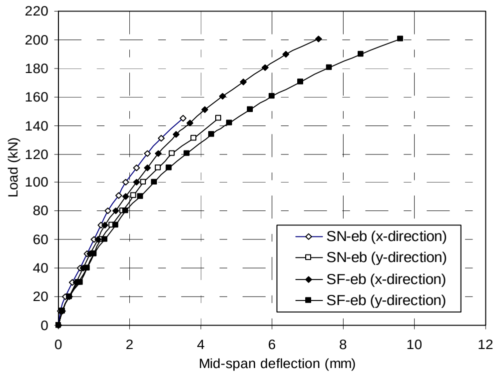


specimens with the square cross section

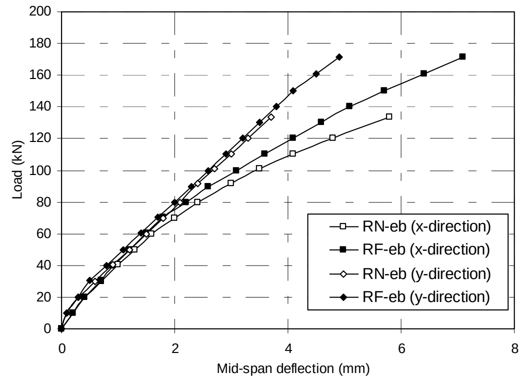


specimens with the rectangular cross section

Figure 4. Load-strain relationships of the concentrically loaded columns



specimens with the square cross section



specimens with the rectangular cross section

Figure 5. Load-lateral deflection relationships of the columns tested under biaxial eccentric loading

Under biaxial eccentric loading, the deflections in the direction of each principal axis for the columns with the square cross section were similar because the cross section was symmetric and the load eccentricity ratio in each direction was the same. For the columns with the rectangular cross section, the deflections in the direction of each principal axis were almost identical until the load reached a value that corresponded to about 50% of the column's load capacity, after which load the deflection in the weak direction (x-direction) tended to increase at a higher rate relative to the deflection in the strong direction (y-direction). The load capacity of the columns tested under biaxial eccentric loading was about one third of the load capacity of the columns tested under concentric loading. It is interesting, however, to note that the gain in the load capacity caused by the CFRP wrapping under biaxial eccentric loading was comparable to that recorded under concentric loading. For the square cross section, with $e_x/b = e_y/h = 0.3$, the CFRP wrapping resulted in about 38% increase in the load capacity whereas about 28% strength gain was recorded for the rectangular cross section under the same eccentricity ratio ($e_x/b = e_y/h = 0.3$). The gain in the load capacity caused by the CFRP under biaxial eccentric loading was comparable to that recorded under concentric loading maybe because the compressed zone of the section under biaxial eccentric loading was surrounded by a column's corner that was highly confined by CFRP. The deflection capacity of the square section wrapped with CFRP was about 2 times that of the unwrapped column whereas for the rectangular column, only 27% increase in the deflection capacity was recorded. It is worth noting that, under biaxial eccentric loading, the columns wrapped with CFRP exhibited an ultimate compressive strain of up to 0.0062. This value was about 1.5 times the maximum ultimate compressive strain recorded for the unwrapped columns (0.004) tested under biaxial eccentric loading which confirms the confinement effectiveness caused by the CFRP under biaxial eccentric loading.

4. ANALYTICAL FORMUALTION

In the analytical modeling, the stress-strain relationship of an unconfined concrete in compression is described by a parabolic relationship. The CFRP-confined concrete stress-strain model developed by Lam and Teng 2003 and recommended by the ACI 440.2R (2008) is adopted in the current analytical work. The stress-strain relationship of steel in tension and compression is idealized to be linear elastic with a post-yield strain hardening of 1%. For a cured CFRP composite sheet, the stress-strain relationship is idealized to be linear-elastic up to failure. The distributions of the strains and the stresses along the diagonal of a symmetrically reinforced square cross-section with equal eccentricity along each principal axis ($e_x = e_y$) under biaxial eccentric loading are shown in Figure 6. For such a section, the neutral axis is perpendicular to the diagonal of the column cross-section in the direction of loading. As shown in Figure 6, the strain ε_z at any distance z from the neutral axis is given by:

$$\varepsilon_z = \frac{z}{c}\ \varepsilon_{c,max} \tag{1}$$

where, c = depth of the neutral axis and $\varepsilon_{c,max}$ = compressive strain at the extreme compression fiber. For unconfined columns, $\varepsilon_{c,max}$ = ε_{cu} = 0.003 (ACI 318-05), whereas for CFRP-confined columns, $\varepsilon_{c,max}$ = ε_{ccu} that is the ultimate strain of CFRP-confined concrete determined as per the ACI 440.2R (2008). Equilibrium conditions are imposed in terms of axial force, P_n, and bending moment, M_n. In order to calculate sectional forces, the cross-section is discretized into finite layers. The steel reinforcing bars are represented by discrete elements. The compression force in concrete is calculated by numerical integration of forces in each layer. Equilibrium equations at failure are then given by:

$$\sum_{i=1}^{n} f_{ci}A_i + \sum A_{si}f_{si} = P_n \tag{2}$$

$$\sum_{i=1}^{n} f_{ci}A_i d_i + \sum A_{si}f_{si}\, d_{si} = M_n \tag{3}$$

where, f_{ci} = concrete stress at the center of the layer i, A_i = area of the layer i, A_{si} = cross-sectional area of the steel bar $_i$, f_{si} = stress in the steel bar i, d_i = distance between the plastic centroid of the cross-section and the centroid of the layer i in a direction perpendicular to the neutral axis, and d_{si} = distance between the plastic centroid of the cross-section and the center of the steel bar i in a direction perpendicular to the neutral axis. In these equations, compressive stresses are taken as positive and tensile stresses are taken as negative. The distances d_i and d_{si}, are taken as positive if the corresponding concrete layer and steel rebar are located above the diagonal of the cross section passing through the plastic centroid in a direction normal to the direction of loading.

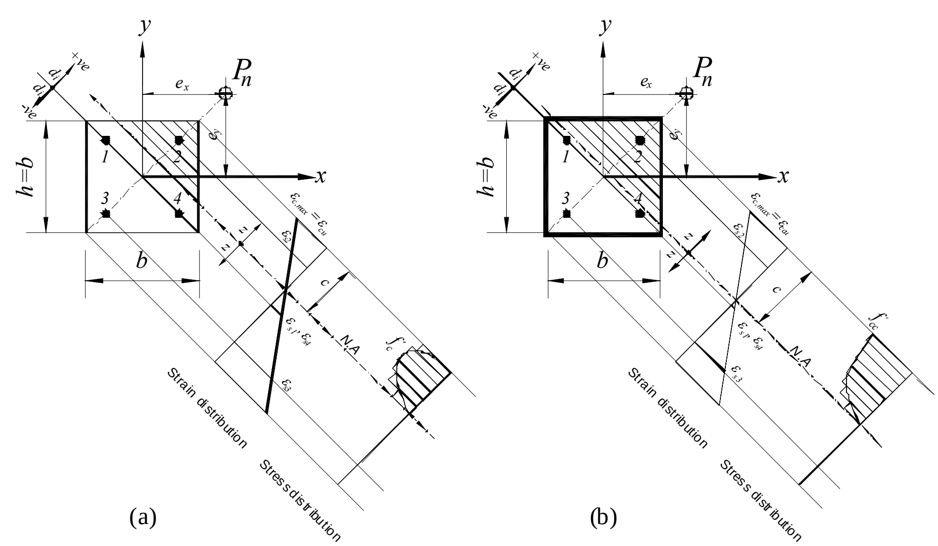


Figure 6. Distribution of strains and stresses for a symmetric square cross-section under biaxial eccentric loading; (a) unconfined section, (b) CFRP-confined section

The model procedures used to predict the load capacity at a given external eccentricity are:

- For a given external eccentricity along the diagonal of the cross section e_{ext}, assume the depth of the neutral axis c.
- Calculate the strains and stresses in the concrete layers and steel rebars according to the strain compatibility requirements and the constitutive material laws.
- Calculate the axial compression force P_n and the bending moment M_n that satisfy equilibrium requirements.
- Calculate the internal eccentricity $e_{int} = M_n / P_n$ and compare it to the external eccentricity e_{ext}.
- Iterate the assumed neutral axis depth c until $e_{int} = e_{ext}$ then record the load capacity.

For rectangular and non-symmetric square cross-sections subjected to biaxial eccentric loading, the problem becomes more complex because the inclination of the neutral axis is not known. If the load capacities of the column under uniaxial eccentricity along each principal axis are determined independently along with the load capacity under concentric axial loading, the load capacity under biaxial eccentric loading can then be computed using the reciprocal load equation developed by Bresler (1960).

$$\frac{1}{P_{nb}} = \frac{1}{P_{nx}} + \frac{1}{P_{ny}} - \frac{1}{P_{no}} \tag{4}$$

where, P_{nx} = load capacity under uniaxial eccentricity in x-direction (e_y = 0), P_{ny} = load capacity under uniaxial eccentricity in y-direction (e_x = 0), and P_{no} = load capacity under concentric axial loading. The model procedure described earlier is used to calculate the load capacity under uniaxial eccentricity along each principal axis, P_{nx} and P_{ny}, independently. The column load capacity under concentric axial loading, P_{no}, can be calculated as follows:

$$P_{no} = \begin{cases} f_c' \ (A_g - A_{st}) + A_{st} f_{so} & \quad unconfined\ columns \\ f_{cc}'(A_g - A_{st}) + A_{st} f_{sc} & \quad C\ FRP\ confined\ columns \end{cases} \tag{5}$$

where, A_{st} = total area of the longitudinal steel, f_{so} = steel stress corresponding to a steel strain of ε_{co} (strain of unconfined concrete corresponded to f_c') but not greater than the ultimate steel strength, and f_{sc} = steel stress corresponding to a steel strain of ε_{ccu} but not greater than the ultimate steel strength. Table 2 shows a comparison between the experimental and analytical results. It is evident that the analytical approach gives good prediction for the load capacity which confirms its accuracy and validity.

Table 2. Analytical verification

Group	Specimen	Experimental load capacity (kN)	Analytical load capacity (kN)	Error (%)
[A]	SN-e0	441.5	471.9	+7
	SF-e0	594.8	581.1	-2
	RN-e0	428	467.5	+9
	RF-e0	558.7	555.5	-0.5
[B]	SN-eb	145	133.8	-8
	SF-eb	200.4	159.5	-20
	RN-eb	133.7	124.75	-7
	RF-eb	171.5	158.75	-7

5. SUMMARY AND CONCLUSION

The performance under biaxial eccentric loading is affected by combined influence of the cross-sectional shape and the CFRP-confinement. For a square cross-section (135x135 mm), with $e_x/b = e_y/h = 0.3$, one layer of CFRP resulted in about 38% increase in the load capacity whereas about 28% gain in load capacity was recorded for a rectangular cross-section (120x150 mm) under the same eccentricity ratio ($e_x/b = e_y/h = 0.3$). The lateral mid-height displacement at peak load of the CFRP-confined column with the square cross-section was about two times that of a similar unconfined column under biaxial eccentric loading. For the CFRP-confined column with the rectangular cross-section, about 27% average increase in the lateral mid-height displacement at peak load was recorded under biaxial eccentric loading. An analytical approach for prediction of the load carrying capacity of CFRP-confined columns under biaxial eccentric loading was presented and verified against test results.

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